Call for 2021 Annual Meeting Proposals

GSA TODAY

THE GEOLOGICAL SOCIETY
OF AMERICA®

VOL. 30, NO. 12 | DECEMBER 2020

The Mesoproterozoic Single-Lid Tectonic Episode: Prelude to Modern Plate Tectonics

THE
GEOLOGICAL
SOCIETY
OF AMERICA®

The Mesoproterozoic Single-Lid Tectonic Episode: Prelude to Modern Plate Tectonics

Robert J. Stern, *Geosciences Dept., The University of Texas at Dallas, Box 830688, Richardson, Texas 75083-0688, USA*

ABSTRACT

The hypothesis that the Mesoproterozoic (1600–1000 Ma) tectonic regime was a protracted single-lid episode is explored. Single-lid tectonic regimes contrast with plate tectonics because the silicate planet or moon is encased in a single lithospheric shell, not a global plate mosaic. Single-lid tectonics dominate among the Solar System's active silicate bodies, and these show a wide range of magmatic and tectonic styles, including heat pipe (Io), vigorous (Venus), and sluggish (Mars). Both positive and negative evidence is used to evaluate the viability of the Mesoproterozoic single-lid hypothesis. Four lines of positive evidence are: (1) elevated thermal regime; (2, 3) abundance of unusual dry magmas such as A-type granites and anorthosites; and (4) paucity of new passive continental margins. Negative evidence is the lack of rock and mineral assemblages formed by plate-tectonic processes such as ophiolites, blueschists, and ultra high-pressure terranes. Younger plate-tectonic–related and Mesoproterozoic mineralization styles contrast greatly. Paleomagnetic evidence is equivocal but is permissive that Mesoproterozoic apparent polar wander paths of continental blocks did not differ significantly. These tests compel the conclusion that the Mesoproterozoic single-lid hypothesis is viable.

INTRODUCTION

Earth's modern plate-tectonic regime emerged from earlier tectonic regimes (Sleep, 2000; Cawood et al., 2018; Stern, 2018; Holder et al., 2019). This paper tests the hypothesis that the Mesoproterozoic was a protracted single-lid tectonics. Below, I briefly outline what single-lid tectonics is before presenting positive and negative evidence to test this hypothesis and explore some implications.

PLATE TECTONICS AND SINGLE-LID TECTONICS

Five concepts are central to this paper:

1. Active silicate bodies have convecting mantles. Tectonics is the lithospheric expression of mantle convection.
2. Plate tectonics is lithosphere divided into a mosaic of strong plates, which move on and sink into weaker ductile asthenosphere as a result of subduction. Plates move relative to each other across three types of boundaries: divergent, convergent, and transform (Bird, 2003). The negative buoyancy of old dense oceanic lithosphere sinking in subduction zones mostly powers plate movements (Forsyth and Uyeda, 1975).
3. Single-lid tectonics contrasts with plate tectonics by having a single, unfragmented, all-encompassing lithosphere.
4. There are many types of single-lid behavior but only one type of plate tectonics (Fig. 1).
5. We are only beginning to explore the range of active silicate body single-lid behaviors, and terminology is confusing. O'Neill and Roberts (2018) refer to stagnant, sluggish, plutonic squishy, or heat pipe variants, whereas Fischer and Gerya (2016) refer to plume-lid tectonics. "Sagduction"—the vertical sinking of weak lithosphere—is another vigorous non-plate tectonic–style (Nédélec et al., 2017).

In 2015 we finished taking a first look at all of the large (= semi-spherical) bodies in the Solar System using a variety of spacecraft (Stern et al., 2018). Four out of five tectonically active silicate bodies in the Solar System show single-lid behavior; that is, they have an all-encompassing lithospheric lid (Stern et al., 2018): Venus and Mars and the two Jovian inner moons, Io and Europa. We have imaged the surfaces of Venus, Mars and Io, but not Europa because it is encased in an icy shell. Venus, Mars, and Io show a wide range of single-lid tectonic behaviors. Io is subjected to strong tidal forces from Jupiter, which heats its interior so that it is very active volcanically and tectonically (McGovern et al., 2016). Io is characterized by heat pipe volcanism, where basaltic layers erupted from randomly distributed volcanoes are buried and remelted a few kilometers below the surface. Venus exhibits vigorous single-lid behavior dominated by mantle plumes and rifts (Ghail, 2015); the upward magma flux is presumably matched by drips and delamination. Mars is a good example of sluggish single-lid behavior, with a few great volcanoes and one great rift.

From studying other active silicate bodies of the Solar System we have learned three important things: (1) there are two distinct tectonic styles: single lid and plate tectonics; (2) there are many single-lid tectonic styles; and (3) only Earth has plate tectonics. Because single-lid tectonics is so common among active silicate bodies, it seems likely that Earth experienced single-lid tectonic episodes in the past.

THE MESOPROTEROZOIC

The Mesoproterozoic (1600–1000 Ma) is the heart of the "Boring Billion," a term coined by Holland (2006) for the interval between 1.85 and 0.85 Ga when atmospheric oxygen levels changed little (Fig. 2A). The term "Boring Billion" is now used to describe many more aspects about this time period than Holland (2006) intended. Cawood and Hawkesworth (2014) called this "Earth's middle age" and marshalled evidence that the Mesoproterozoic was a time of environmental, evolutionary, and lithospheric stability distinct from the dramatic changes documented for other times.

I have argued elsewhere (Stern, 2005; Stern, 2018) that Earth's modern plate-tectonic regime began in Neoproterozoic time. If Earth did not have plate tectonics, it had some type of single-lid tectonics. Earth has always experienced deformation and magmatism, but studying Io, Venus, and Mars shows that this could have been caused by single-lid as well as plate tectonics. An active silicate body's tectonic evolution is likely to be complicated, with multiple different episodes. Earth may have ex-

---

GSA Today, v. 30, https://doi.org/10.1130/GSATG480A.1. CC-BY-NC.

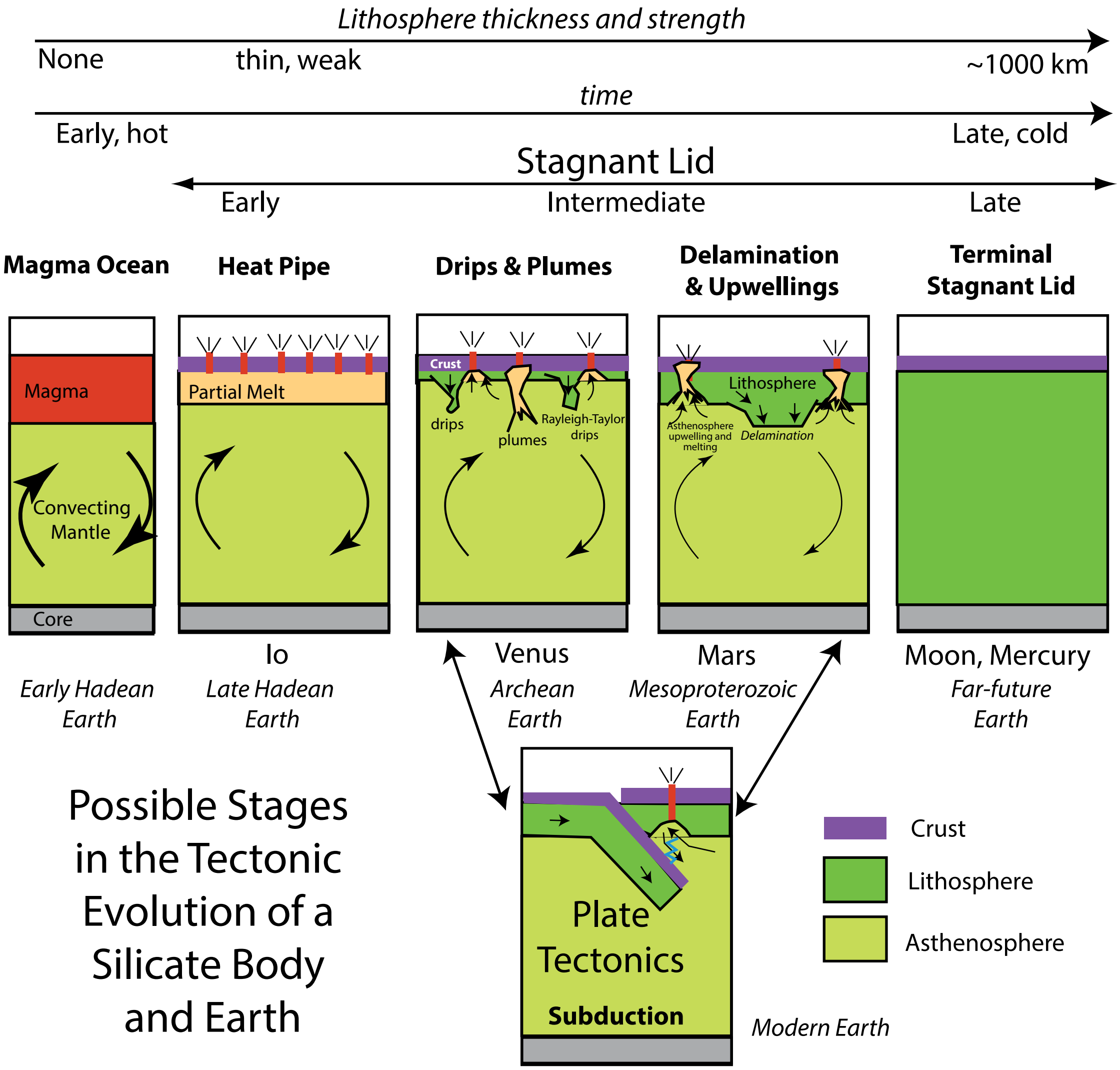

Figure 1. Possible evolution of magmatotectonic styles for a large silicate body like Earth. Examples from active Solar System bodies Io, Venus, and Mars are shown. Possible evolution of Earth is also shown. Strength of mantle convection is indicated by arrowed curve thickness. Plate tectonics requires certain conditions of lithospheric density and strength in order to occur and is likely to be presaged and followed by different styles of stagnant lid tectonics. See text for further discussion. Modified after Stern et al. (2018).

perienced multiple episodes of different kinds of single-lid behavior and of plate tectonics. Different tectonic regimes produce different structures, metamorphic rocks, and igneous rocks that, if preserved, provide evidence about the tectonic regime that produced them. Erosion, alteration, and burial destroy some but not all of the evidence of past tectonic regimes, at least for the past 3 Ga. Erosion may remove shallow features such as porphyry copper deposits and ophiolite nappes but cannot extirpate intrusive and metamorphic rocks, which extend to depth. Microscopic, geochemical, and isotopic evidence is useful for identifying when a change occurred in Earth's convective style but cannot reliably constrain when plate tectonics began. Condie's (2018, p. 58) admonition "… recycling of crust into the mantle does not necessarily require subduction, and it may be possible for such recycling to occur in stagnant [single]-lid regimes…" should be kept in mind.

EVIDENCE THAT THE MESOPROTEROZOIC WAS A PROTRACTED SINGLE-LID EPISODE

Geologic evidence—both negative and positive—should guide our interpretation of Mesoproterozoic tectonics. Negative evidence shows an absence of key plate-tectonic indicators (Figs. 2B–2D). Positive evidence specifies geologic features expected for single-lid behavior (Figs. 2E–2H). The first approach is straightforward because we know the kinds of rocks produced by plate tectonics. The second approach is more difficult because we are only beginning to think about what kinds of rocks should be produced by active single-lid tectonics.

Consider the negative evidence first. Stern (2018) identified three groups of rocks and minerals that only form by plate-tectonic processes. These are (1) ophiolites, indicators of subduction initiation and seafloor spreading; (2) blueschists, lawsonite-bearing metamorphic rocks, and jadeitite, indicators of subduction; and (3) ultra-high pressure (UHP) metamorphic rocks along with ruby and sapphire, indicators of continent-continent collision (Figs. 2B–2D). All of these are abundant in Phanerozoic and Neoproterozoic time and all are missing from the Mesoproterozoic. Brown and

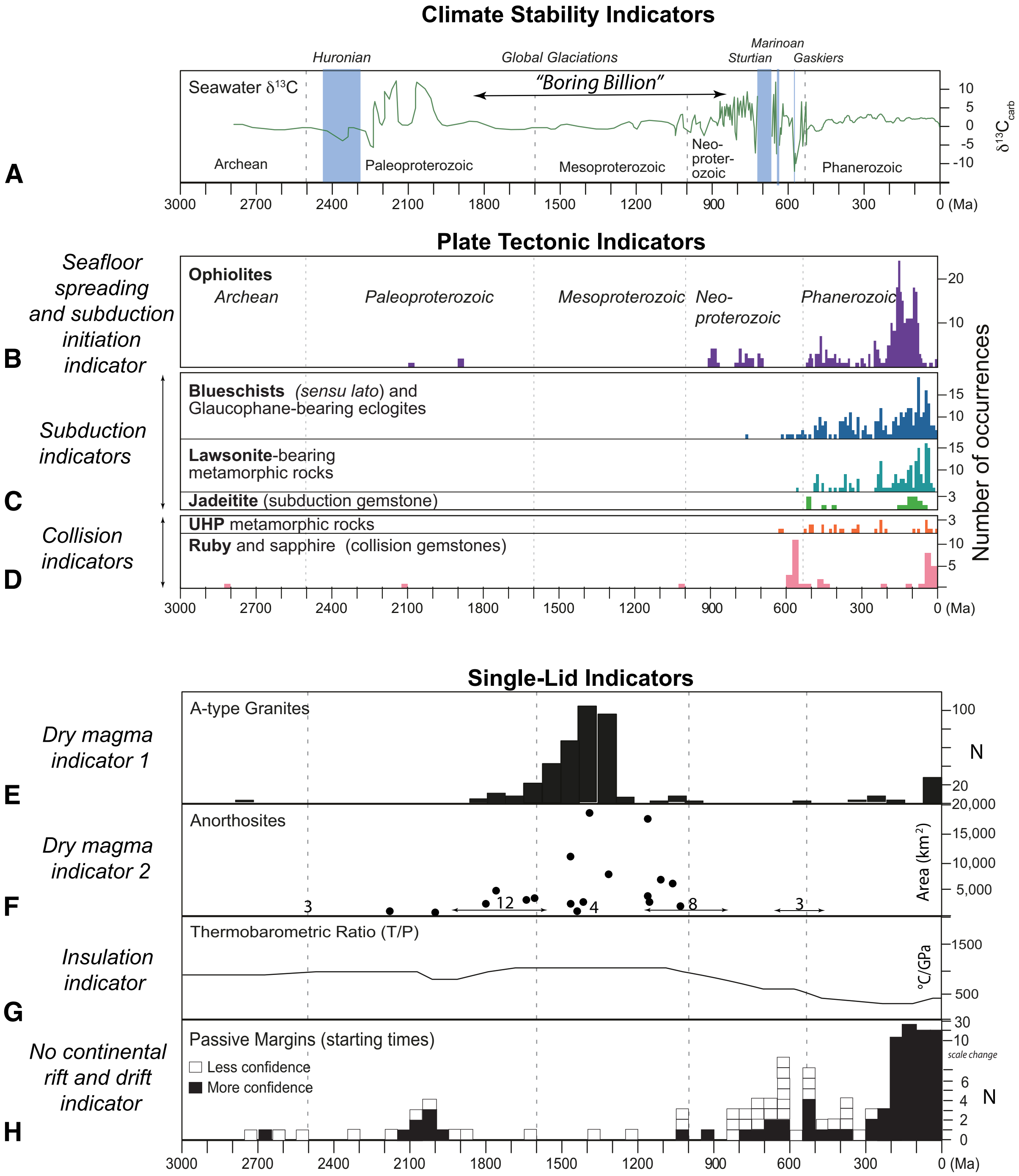

Figure 2. (A) Climate, (B–D) plate-tectonic, and (E–H) single-lid indicators for the past 3.0 Ga of Earth's history. Climate stability and plate-tectonic indicators from Stern (2018). "Boring Billion" from Holland (2006). Single-lid tectonic indicators include (E) A-type granites (Condie, 2014), (F) massif-type anorthosites (Ashwal, 2010), (G) thermobarometric ratios ($n = 564$; best fit curve from Brown et al., 2020), and (H) numbers of passive continental margins (Bradley, 2011). Fourfold confidence subdivision of Bradley (2011) is simplified into two intervals of higher and lower confidence. UHP—ultra-high pressure.

Johnson (2018) compiled data for 456 metamorphic terranes from the Eoarchean to the Cenozoic and classified these into three groups. Low dT/dP (which approximates the geothermal gradient at the time of metamorphism) metamorphic environments correspond to blueschist and eclogite, metamorphic rocks that only form in subduction zones. There are a few low dT/dP metamorphic rocks ca. 1.9 Ga but almost none in the Mesoproterozoic. There are a lot of Neoproterozoic and Phanerozoic low dT/dP metamorphic terranes. An independent assessment by Palin et al. (2020) confirms that there were two great episodes of low dT/dP metamorphism: one at 1.8–2.1 Ga and the second episode that began 0.7 Ga and continues today.

Positive evidence for single-lid behavior includes three types of indicators: (1) geochemical evidence of unusual, dry magmatism; (2) metamorphic evidence of elevated heat flow; and (3) sedimentological evidence for formation of passive continental margins. These are considered in greater detail below.

Because plate tectonics and subduction zones deliver large quantities of water deep into the mantle (van Keken et al., 2011) and single-lid episodes deliver less water, magmas generated during single-lid episodes should be drier than arc magmas generated by plate tectonics. I-type granitic rocks should dominate during plate tectonic regimes. In contrast, A-type granitic rocks are anhydrous, alkali-rich, and anorogenic (dall'Agnol et al., 2012). Mesoproterozoic A-type granites are unusually abundant compared to earlier and later times (Fig. 2E).

Massif-type anorthosites are another positive single-lid indicator that reflect anhydrous magmas. These were rarely emplaced in Neoproterozoic and Phanerozoic times but were placed abundantly in the Mesoproterozoic (Fig. 2F). Mesoproterozoic anorthosites may reflect deep-crustal ponding of basaltic magmas, crystallization and sinking of mafic silicates, and flotation of plagioclase in an Fe-rich magma (Namur et al., 2011; Ashwal and Bybee, 2017). Formation of Fe-rich magmas requires fractionation under low-oxygen fugacity conditions (Skaergaard trend). Low-oxygen fugacities are associated with dry magmas, not those generated above subduction zones (Cottrell et al., 2021).

A second line of positive evidence is that the lithosphere heated up. This is shown by the metamorphic thermobaric ratios (temperature/pressure, *T/P*) for Paleoarchean to Cenozoic metamorphic rocks (Brown et al., 2020). Thermobarometric ratios over the past 3.0 Ga are highest for Mesoproterozoic time (Fig. 2G). Heating up of the upper mantle (and the overlying lithosphere) is expected for single-lid tectonic regimes. Plate tectonics better cools Earth because it injects cold lithosphere deep into the mantle in subduction zones at the same time it releases asthenospheric heat at spreading ridges. An all-encompassing single lid, in contrast, insulates the interior and traps heat in the asthenosphere. Heat release is accomplished by magmatic outbursts and thinning the lithosphere (van Thienen et al., 2005). Lithospheric thinning leads to an elevated thermal gradient that is preserved in metamorphic rocks.

The third line of evidence is the paucity of new passive continental margins that formed in Mesoproterozoic time (Fig. 2H; Bradley, 2011). Passive continental margins form when continents rift and drift apart. They form frequently in a plate-tectonic regime but not in a single-lid tectonic regime.

There are distinctive Mesoproterozoic ore deposits that do not form in younger times when we can be confident that plate tectonics occurred, including sedimentary rock-hosted U, Kiruna magnetite-apatite, iron oxide-copper-gold, and ilmenite ore deposits. Correspondingly, the Mesoproterozoic lacks ore deposits that are common to younger assemblages formed by plate-tectonic processes such as orogenic gold and porphyry copper deposits (Goldfarb et al., 2010). Different mineralization styles are expected to accompany different tectonic styles. The contrast between younger plate tectonic–related and Mesoproterozoic mineralization styles couldn't be greater, which is consistent with an interpretation of different tectonic styles for these intervals.

Finally, there is paleomagnetic evidence. Paleomagnetic measurements could resolve the controversy because single-lid behavior should show that all continental blocks moved together. Unfortunately, paleomagnetic data that bear on this question are equivocal. Evans and Mitchell (2011) compiled and reported new paleomagnetic data and used these to conclude that there were "… minimal paleogeographic changes across Earth's first supercontinent cycle, in marked contrast to the dramatic reorganization implied between such Rodinia configurations and the subsequent assembly of Gondwana" (p. 445). This is consistent with the compilation of O'Neill et al. (2013), who found low plate-motion velocities through Early and Middle Mesoproterozoic time, although a rapid increase in plate velocity was noted for Late Mesoproterozoic time (see Discussion). On the basis of an independent compilation of paleomagnetic data, Piper (2013) identified the 1.7–1.25 Ga time period as a single-lid episode. Piper (2013) further inferred from paleomagnetic evidence that the transition to modern plate tectonics began ca. 1.1 Ga. These conclusions are controversial; for example, Pisarevsky et al. (2014) argue that Nuna/Columbia assembled by 1600 Ma and broke up at 1400 Ma. Meert and Santosh (2017) noted that "… despite the exponential increase in available [paleomagnetic] data, knowledge of the assembly, duration and breakup history of the supercontinent are contentious" (p. 67). Clearly, more paleomagnetic work is needed to resolve this controversy.

DISCUSSION

Given that plate tectonics emerged from a single-lid episode, how does this happen and how long does it take? Studies of Io, Venus, and Mars' single-lid episodes compel the conclusion that plate tectonics is a "Goldilocks" tectonic style. Oceanic lithosphere must be strong and dense, but not too strong or it cannot break to form new subduction zones; too weak and the lithosphere will break off in subduction zones. Single-lid tectonic regimes dominate when conditions for plate tectonics do not exist and when a lid with appropriate strength and density cannot be ruptured to form the first subduction zone, spreading ridge, and transform faults.

Sleep (2000) explored how an active silicate planet was likely to evolve through three different tectonic styles as a result of changing heat flow and mantle potential temperature: magma ocean, plate tectonics, and single-lid behavior. Magma ocean only happens early in planetary evolution, but cycling between plate tectonics and single lid may happen after that. Specifically, as plate tectonics cools the planet, lithosphere thickens and strengthens, ultimately transitioning into single lid. Single-lid regimes insulate the mantle, trapping heat and leading to lithospheric weakening, favoring plate tectonics.

O'Neill et al. (2016) argued that Earth may have started in an Io-like heat-pipe tectonic regime that evolved into short-lived alternating single-lid and plate-tectonic regimes over the next few billions of years (Fig. 1). As Earth-like planets cool, they may evolve into a plate-tectonic regime before eventually decaying into a terminal single-lid regime. The evidence presented here suggests that the Mesoproterozoic era was one such single-lid episode, separating an episode of Paleoproterozoic plate tectonics from the modern episode that began in Neoproterozoic time.

Evidence for cycling between single-lid and plate-tectonic styles is preserved in the rock record. Preservation of some ca. 1.8–2.0 Ga ophiolites and low dT/dP metamorphic belts indicates a brief plate-tectonic interval during this time. This episode ended with formation of a supercontinent called Columbia (Rogers and Santosh, 2002) or Nuna (Hoffman, 1997) and Earth entered the Mesoproterozoic single-lid episode. Immediately after a supercontinent forms is optimal for establishing a single-lid tectonic regime because supercontinent assembly destroys subduction zones between them to stop plate tectonics (Silver and Behn, 2008). Silver and Behn argued that formation of the Columbia/Nuna supercontinent led to the Mesoproterozoic single-lid episode.

Given the wide range of possible single-lid behaviors, how should we characterize the Mesoproterozoic episode? There was little orogenic activity during especially the first two-thirds of Mesoproterozoic time (Fig. 3). There was significant if unusual igneous activity but a low rate of crustal growth; Brown and Johnson (2018) infer that Mesoproterozoic crustal growth rates were 20%–50% that of other eons/eras. The Mesoproterozoic single-lid episode seems to have been somewhat between the vigorous style of Venus and the sluggish style of Mars today; perhaps "ponderous" single lid is an apt description.

THE GRENVILLE OROGENY AND MIDCONTINENT RIFT SYSTEM

The end of Mesoproterozoic differs significantly from the beginning and the middle. In Early and Middle Mesoproterozoic time there was a lot of igneous activity but little deformation, while the Late Mesoproterozoic experienced much more deformation (Figs. 3–4; Condie et al., 2015). Late Mesoproterozoic orogeny is known as Grenville in North America, Kibaran in Africa, and Sveconorwegian or Dalslandian in Europe. All of these expressions of ca. 1.2–0.95 Ga compressional deformation are called the "Global Grenville Orogeny" (GGO here for brevity). The GGO is generally accepted to manifest continental collisions to form the supercontinent Rodinia (Li et al., 2008). If this interpretation is correct, then plate tectonics operated in earlier Mesoproterozoic time, falsifying the central hypothesis that the Mesoproterozoic was a single-lid tectonic episode. Are there alternative explanations for the GGO that are consistent with a Mesoproterozoic single-lid episode? I think so. We know that few plate-tectonic indicators are associated with the GGO (Figs. 2B–2D), suggesting that it was somehow different than younger continental collision events, where such evidence is preserved.

Another difference between the GGO and younger continental collisions is that GGO compression was coeval with strong foreland extension and large igneous province (LIP) formation. This is best shown by the Mid-Continent Rift System (MCRS) of North America. The MCRS is at least 3000-km long, comparable to the modern East African and Baikal rifts, but is not a linear rift. Instead, it defines an upside-down "U" centered on Lake Superior with one arm that can be traced southwestward continuously as far as Kansas and discontinuously as far as west Texas and another arm that extends southeastward at least through Michigan. Stein et al. (2015) contrast the MCRS gravity signature with that of other continental rifts that have negative gravity anomalies because they are mostly filled with low-density sediment. Instead, the MCRS is filled with mostly mafic igneous rocks. Modeling of seismic and gravity profiles across the MCRS indicates a total magma volume of ~1–2 × 10^6 km^3 (Merino et al., 2013), an order of magnitude larger than the threshold for large igneous provinces (10^5 km^3) defined by Ernst (2014).

The MCRS trends discontinuously south in the subsurface from Kansas into west Texas, where igneous rocks can be traced south into the buried GGO deformation front. MCRS-related igneous rocks can be identified farther west. Late Mesoproterozoic (1140–1040 Ma) mafic and felsic magmatism affected a broad, ~1500-km-long region along the southwestern U.S. (Bright et al., 2014). Similar igneous suites are found elsewhere around the globe, including the 1078–1070 Ma Warakurna LIP of Australia, the 1112–1102 Ma Umkondo LIP in southern Africa, and mafic intrusions in Bolivia and northern India (Bright et al., 2014).

The relationship between global occurrences of the 1200–980 Ma GGO and 1150–1040 Ma LIP is unclear. Stein et al. (2018) argue that much of what has been called "Grenville" in the U.S. is actually buried MCRS. I concur with their assessment that the GGO and Late Mesoproterozoic LIPs need to be considered together, evidence that important changes happened in the solid Earth system at that time. I also conclude that the unusual nature of the GGO—including its lack of plate-tectonic indicators and association with coeval LIPs—indicates that consideration of a non–plate-tectonic origin for this activity is warranted. It is beyond the scope of this paper to explore in depth what that origin was, but the evidence for strong coeval compression, and extension suggests that the Late Mesoproterozoic GGO-LIP system marks the beginning of the transition from Mesoproterozoic single-lid to Neoproterozoic and younger plate tectonics.

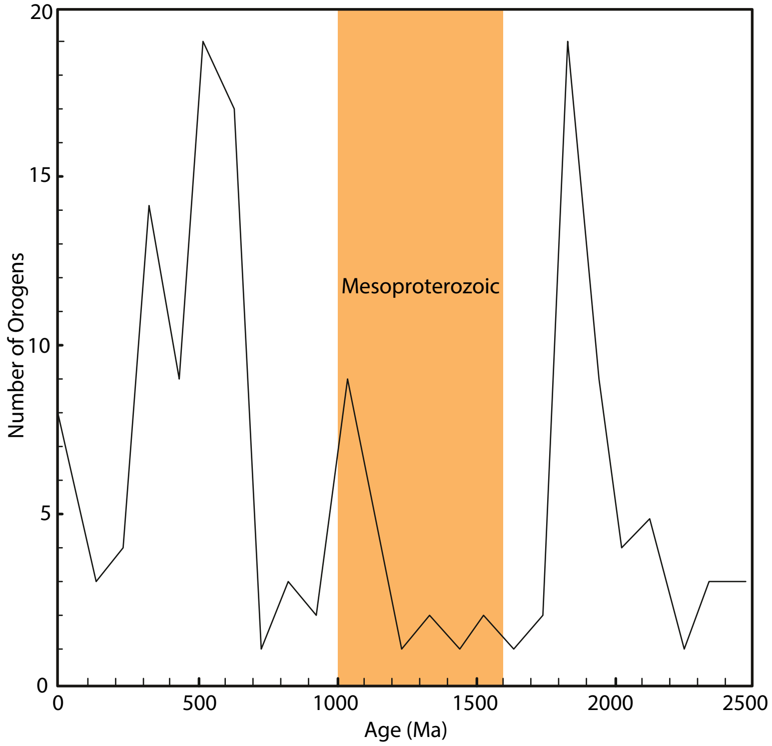

Figure 3. Numbers of orogens through time back to 2.5 Ga; from Condie et al. (2015).

CONCLUSIONS

Solar System exploration shows that most active silicate bodies have some kind of single-lid tectonic style and that only Earth has plate tectonics. Single-lid tectonic styles can range widely and will evolve from more to less deformation and magmatism as the body cools. Single-lid tectonic regimes can evolve

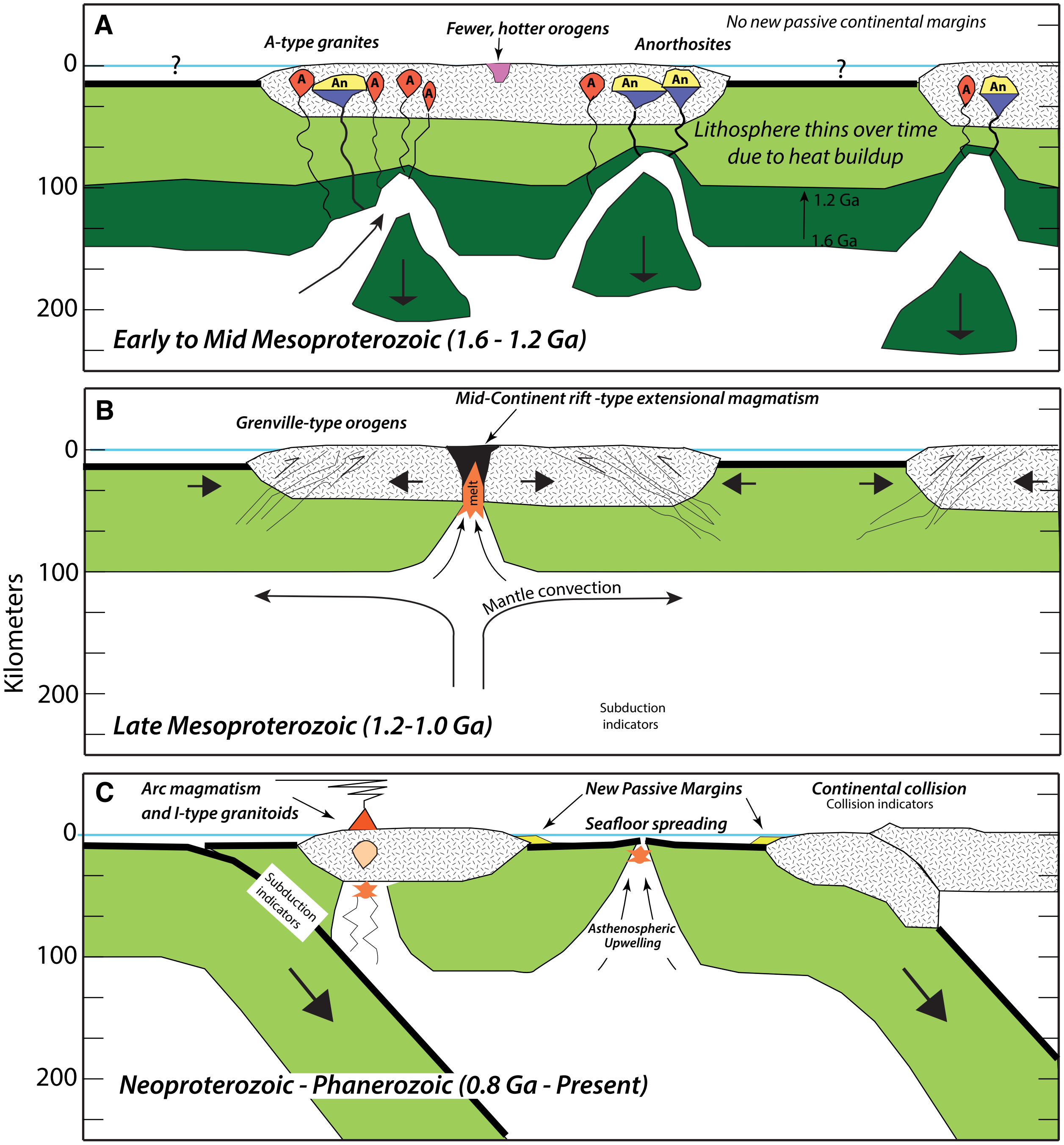

Figure 4. Cartoon showing three tectono-magmatic episodes and key characteristics of each discussed in this paper. (A) Early to Mid-Mesoproterozoic single-lid episode; (B) Late Mesoproterozoic regime; and (C) Neoproterozoic and younger plate-tectonic regime. A—A-type granites; An—anorthosite.

into plate tectonics. We can't understand the evolution of plate tectonics without better understanding Earth's episodes of single-lid behavior, when these were, and what the magmatic and tectonic styles of each were. The single-lid tectonic history of our planet needs to be explored if we are to understand how the modern solid Earth came to be. Negative evidence that plate tectonics did not occur should be combined with positive evidence for a single-lid tectonic regime. The Mesoproterozoic is the best interval of Earth history for this exploration to begin.

ACKNOWLEDGMENTS

Without Kent Condie's help, I wouldn't know how to start to think about the Mesoproterozoic. Also, thanks to Jean Bédard, Peter Cawood, and an anonymous referee for incisive reviews of an earlier version of this manuscript, to Jerry Dickens for suggesting that *GSA Today* might be a good place to publish this paper, to Peter Cawood for a second review, and to Mihai Ducea for speedy editorial handling. This is University of Texas at Dallas geosciences contribution #1376.

REFERENCES CITED

Ashwal, L.D., 2010, The temporality of anorthosites: Canadian Mineralogist, v. 48, p. 711–728, https://doi.org/10.3749/canmin.48.4.711.

Ashwal, L.D., and Bybee, G.M., 2017, Crustal evolution and the temporality of anorthosites:

Earth-Science Reviews, v. 173, p. 307–330, https://doi.org/10.1016/j.earscirev.2017.09.002.

Bird, P., 2003, An updated digital model of plate boundaries: Geochemistry, Geophysics, Geosystems, v. 4, no. 3, p. 1027–1079, https://doi.org/10.1029/2001GC000252.

Bradley, D., 2011, Secular trends in the geological record and the supercontinent cycle: Earth-Science Reviews, v. 108, p. 16–33, https://doi.org/10.1016/j.earscirev.2011.05.003.

Bright, R.M., Amato, J.M., Denyszyn, S.W., and Ernst, R.E., 2014, U-Pb geochronology of 1.1 Ga diabase in the southwestern United States: Testing models for the origin of a post-Grenville large igneous province: Lithosphere, v. 6, p. 135–156, https://doi.org/10.1130/L335.1.

Brown, M., and Johnson, T., 2018, Secular change in metamorphism and the onset of global plate tectonics: The American Mineralogist, v. 103, p. 181–196, https://doi.org/10.2138/am-2018-6166.

Brown, M., Kirkland, C.L., and Johnson, T.E., 2020, Evolution of geodynamics since the Archean: Significant change at the dawn of the Phanerozoic: Geology, v. 48, p. 488–492, https://doi.org/10.1130/G47417.1.

Cawood, P.A., and Hawkesworth, C.J., 2014, Earth's middle age: Geology, v. 42, p. 503–506, https://doi.org/10.1130/G35402.1.

Cawood, P.A., Hawkesworth, C.J., Pisarevsky, S.A., Dhuime, B., Capitanio, F.A., and Nebel, O., 2018, Geological archive of the onset of plate tectonics: Philosophical Transactions of the Royal Society Series A, v. 376, no. 2132, https://doi.org/10.1098/rsta.2017.0405.

Condie, K.C., 2014, How to make a continent: Thirty-five years of TTG research, *in* Dilek, Y., and Furnes, H., eds., Evolution of Archean Crust and Early Life: Modern Approaches in Solid Earth Sciences 7: Dordrecht, Netherlands, Springer Science + Business Media, p. 179–193.

Condie, K.C., 2018, A planet in transition: The onset of plate tectonics on Earth between 3 and 2 Ga?: Geoscience Frontiers, v. 9, p. 51–60, https://doi.org/10.1016/j.gsf.2016.09.001.

Condie, K., Pisarevsky, S.A., Korenaga, J., and Gardoll, S., 2015, Is the rate of supercontinent assembly changing with time?: Precambrian Research, v. 259, p. 278–289, https://doi.org/10.1016/j.precamres.2014.07.015.

Cottrell, E., Birner, S., Brounce, M., Davis, F.A., Waters, L.E., and Kelley, K.A., 2021, Oxygen fugacity across tectonic settings, *in* Neuville, D.R., and Moretti, R., eds., Redox Variables and Mechanisms in Magmatism and Volcanism: AGU Geophysical Monograph: Wiley (in press).

dall'Agnol, R., Frost, C.D., and Rämo, O.T., 2012, Editorial: IGCP Project 510 "A-type Granites and Related Rocks through Time": Project vita, results, and contribution to granite research: Lithos, v. 151, p. 1–16, https://doi.org/10.1016/j.lithos.2012.08.003.

Ernst, R.E., 2014, Large Igneous Provinces: Cambridge, UK, Cambridge University Press, 653 p., https://doi.org/10.1017/CBO9781139025300.

Evans, D.A.D., and Mitchell, R.N., 2011, Assembly and breakup of the core of the Paleoproterozoic-Mesoproterozoic supercontinent Nuna: Geology, v. 39, p. 443–446, https://doi.org/10.1130/G31654.1.

Fischer, R., and Gerya, T., 2016, Early Earth plume-lid tectonics: A high-resolution 3D numerical modelling approach: Journal of Geodynamics, v. 100, p. 198–214, https://doi.org/10.1016/j.jog.2016.03.004.

Forsyth, D., and Uyeda, S., 1975, On the relative importance of the driving forces of plate motion: Geophysical Journal International, v. 43, p. 163–200, https://doi.org/10.1111/j.1365-246X.1975.tb00631.x.

Ghail, R., 2015, Rheological and petrological implications for a stagnant lid regime on Venus: Planetary and Space Science, v. 113–114, p. 2–9, https://doi.org/10.1016/j.pss.2015.02.005.

Goldfarb, R.J., Bradley, D., and Leach, D.L., 2010, Secular variation in economic geology: Economic Geology and the Bulletin of the Society of Economic Geologists, v. 105, p. 459–465, https://doi.org/10.2113/gsecongeo.105.3.459.

Hoffman, P.F., 1997, Tectonic genealogy of North America, *in* van der Pluijm, B.A., and Marshak, S., eds., Earth Structure: An Introduction to Structural Geology and Tectonics: New York, McGraw-Hill, p. 459–464.

Holder, R.M., Viele, D.R., Brown, M., and Johnson, T.E., 2019, Metamorphism and the evolution of plate tectonics: Nature, v. 572, p. 378–381, https://doi.org/10.1038/s41586-019-1462-2.

Holland, H.D., 2006, The oxygenation of the atmosphere and oceans: Philosophical Transactions of the Royal Society of London, Series B, Biological Sciences, v. 361, p. 903–915, https://doi.org/10.1098/rstb.2006.1838.

Li, Z.X., Bogdanova, S.V., Collins, A.S., Davidson, A., De Waele, B., Ernst, R.E., Fitzsimons, I.C.W., Fuck, R.A., Gladkochub, D.P., Jacobs, J., Karlstrom, K.E., Lu, S., Natapov, L.M., Pease, V., Pisarevsky, S.A., Thrane, K., and Vernikovsky, V., 2008, Assembly, configuration, and break-up history of Rodinia: A synthesis: Precambrian Research, v. 160, p. 179–210, https://doi.org/10.1016/j.precamres.2007.04.021.

McGovern, P.J., Kirchhoff, M.R.R., White, O.L., and Schenk, P.M., 2016, Magmatic ascent pathways associated with large mountains on Io: Icarus, v. 272, p. 246–257, https://doi.org/10.1016/j.icarus.2016.02.035.

Meert, J.G., and Santosh, M., 2017, The Columbia supercontinent revisited: Gondwana Research, v. 50, p. 67–83, https://doi.org/10.1016/j.gr.2017.04.011.

Merino, M., Keller, G.R., Stein, S., and Stein, C., 2013, Variations in Mid-Continent Rift magma volumes consistent with microplate evolution: Geophysical Research Letters, v. 40, p. 1513–1516, https://doi.org/10.1002/grl.50295.

Namur, O., Charlier, B., Pirard, C., Hermann, J., Liégeois, J.-P., and Auwera, J.V., 2011, Anorthosite formation by plagioclase flotation in ferrobasalt and implications for the lunar crust: Geochimica et Cosmochimica Acta, v. 75, p. 4998–5018, https://doi.org/10.1016/j.gca.2011.06.013.

Nédélec, A., Monnereau, M., and Toplis, M.J., 2017, The Hadean–Archaean transition at 4 Ga: From magma trapping in the mantle to volcanic resurfacing of the Earth: Terra Nova, v. 29, p. 218–223, https://doi.org/10.1111/ter.12266.

O'Neill, C., and Roberts, N.M.W., 2018, Lid tectonics—Preface: Geoscience Frontiers, v. 9, p. 1–2, https://doi.org/10.1016/j.gsf.2017.10.004.

O'Neill, C., Lenardic, A., and Condie, K.C., 2013, Earth's punctuated tectonic evolution: Cause and effect, *in* Roberts, N.M.W., van Kranendonk, M., Parman, S., Shirey, S., and Clift, P.D., eds., Continent Formation through Time: Geological Society, London, Special Publication 389, p. 17–40.

O'Neill, C., Lenardic, A., Weller, M., Moresi, L., Quenette, S., and Zhang, S., 2016, A window for plate tectonics in terrestrial planet evolution?: Physics of the Earth and Planetary Interiors, v. 255, p. 80–92, https://doi.org/10.1016/j.pepi.2016.04.002.

Palin, R.M., Santosh, M., Cao, W., Li, S.-S., Hernández-Uribe, D., and Parsons, A., 2020, Secular metamorphic change and the onset of plate tectonics: Earth-Science Reviews, v. 207, https://doi.org/10.1016/j.earscirev.2020.103172.

Piper, J.D.A., 2013, A planetary perspective on Earth evolution: Lid tectonics before plate tectonics: Tectonophysics, v. 589, p. 44–56, https://doi.org/10.1016/j.tecto.2012.12.042.

Pisarevsky, S.A., Elming, S.-A., Pesonen, L.J., and Li, Z.-X., 2014, Mesoproterozoic paleogeography: Supercontinent and beyond: Precambrian Research, v. 244, p. 207–225, https://doi.org/10.1016/j.precamres.2013.05.014.

Rogers, J.J.W., and Santosh, M., 2002, Configuration of Columbia, a Mesoproterozoic supercontinent: Gondwana Research, v. 5, p. 5–22, https://doi.org/10.1016/S1342-937X(05)70883-2.

Silver, P.G., and Behn, M.D., 2008, Intermittent plate tectonics?: Science, v. 319, p. 85–88, https://doi.org/10.1126/science.1148397.

Sleep, N.H., 2000, Evolution of the mode of convection within terrestrial planets: Journal of Geophysical Research, v. 105, E7, p. 17,563–17,578, https://doi.org/10.1029/2000JE001240.

Stein, C.A., Kley, J., Stein, S., Hindle, D., and Keller, G.R., 2015, North America's Midcontinent Rift: When rift met LIP: Geosphere, v. 11, p. 1607–1616, https://doi.org/10.1130/GES01183.1.

Stein, C.A., Stein, S., Elling, R., Keller, G.R., and Kley, J., 2018, Is the "Grenville Front" in the central United States really the Midcontinent Rift?: GSA Today, v. 28, no. 5, p. 4–10, https://doi.org/10.1130/GSATG357A.1.

Stern, R.J., 2005, Evidence from ophiolites, blueschists, and ultra-high pressure metamorphic terranes that the modern episode of subduction tectonics began in Neoproterozoic time: Geology, v. 33, no. 7, p. 557–560, https://doi.org/10.1130/G21365.1.

Stern, R.J., 2018, The evolution of plate tectonics: Philosophical Transactions of the Royal Society Series A, https://doi.org/10.1098/rsta.2017.0406.

Stern, R.J., Gerya, T., and Tackley, P., 2018, Planetoid tectonics: Perspectives from silicate planets, dwarf planets, large moons, and large asteroids: Geoscience Frontiers, v. 9, p. 103–119, https://doi.org/10.1016/j.gsf.2017.06.004.

van Keken, P.E., Hacker, B.R., Syracuse, E.M., and Abers, G.A., 2011, Subduction factory: 4. Depth-dependent flux of H_2O from subducting slabs worldwide: Journal of Geophysical Research, v. 116, no. B1, B01401, https://doi.org/10.1029/2010JB007922.

van Thienen, P., Vlaar, N.J., and van den Berg, A.P., 2005, Assessment of the cooling capacity of plate tectonics and flood volcanism in the evolution of Earth, Mars and Venus: Physics of the Earth and Planetary Interiors, v. 150, p. 287–315, https://doi.org/10.1016/j.pepi.2004.11.010.

Manuscript received 12 Aug. 2020
Revised manuscript received 10 Sept. 2020
Manuscript accepted 15 Sept. 2020